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OPTICAL SWITCH WITH POWER EQUALIZATION

CROSS-REFERENCES TO RELATED APPLICATIONS

The present application is related in subject matter to co-pending U.S. Patent Application Serial No. 09/511,065 to Graves et al., entitled "Switch for Optical Signals", filed on February 23, 2000, assigned to the assignee of the present invention and hereby incorporated by reference herein in its entirety.

The present application is also related in subject matter to the co-pending U.S. Patent Application entitled "Optical Switch with Connection Verification" to Graves et al., filed on even date, assigned to the assignee of the present invention and hereby incorporated by reference herein in its entirety.

FIELD OF THE INVENTION

The present invention relates generally to systems used for switching optical wavelength channels in a wavelength division multiplexed (WDM) network and, more particularly, to optical switches and cross-connects which are required to be equipped with power equalization functionality for controlling the power of individual carriers in a WDM signal.

BACKGROUND OF THE INVENTION

The principle of wavelength division multiplexing consists of transporting, on a single optical waveguide such as a fiber, a plurality of independent data signals which

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respectively modulate a plurality of optical carriers occupying distinct optical wavelengths. This allows for significant savings when it is desired to increase the capacity of a network that already has optical fiber in place but where the fiber was previously used for transporting only a single optical carrier occupying a single optical wavelength. Since an optical carrier is implicitly associated with an optical wavelength, the expressions "optical carrier" and "optical wavelength" will hereinafter be used interchangeably.

In a wavelength division multiplexed (WDM) network, each optical carrier is associated with its own source and destination nodes. Where multiple optical carriers have intersecting routes, these multiple optical carriers will occupy different wavelengths of light on the same fiber. When this type of multi-carrier signal travels along a long route, amplifiers will be required at every 80 kilometers or so in order to boost the signal's optical power.

On even longer routes, a multi-carrier optical signal may not just suffer severe attenuation but it may also become distorted due to effects such as chromatic dispersion, polarization mode dispersion, signal-to-noise ratio degradation resulting from noise contributions of multiple cascaded amplifiers, and non-linearities in the optical transmission medium or in the optical components traversed along the way.

30 Distortion of this nature is sometimes counteracted by inserting equipment in the optical path for providing dispersion compensation or banded gain equalization. In severe cases of distortion, an array of regenerators may need

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to be added. In its most basic form, a regenerator array detects the data on each incoming carrier and uses the detected digital data to re-modulate a fresh (usually re-shaped and re-synchronized) optical signal on the appropriate optical wavelength. Thus, a regenerator array requires, for each wavelength it is required to regenerate, an optical receiver, electronic re-shaping and re-timing circuitry and an optical source. For a dense wavelength division multiplexing (DWDM) system with typically 32 to 160 wavelengths per fiber, this leads to a very complex regenerator array.

In order to allow the flexible interconnection of optical carriers, an optical network must be equipped with a mechanism for providing switching functionality at the optical carrier level. Traditionally, an optical interconnect mechanism is implemented either as an optical patch panel or as an electrical switch (or cross-connect) with optical-to-electrical converters at its input and electrical-to-optical converters at its output.

A cross-connect differs from an switch in that for the case of a cross-connect, the connection map is usually provisioned from a central network management tool, either automatically or manually, whereas for the case of an optical switch, the connection map can be controlled in real time and may even be controlled by the traffic content through the switch, in which case the switch is said to be self-routing. In the interest of simplicity, and because a switch inherently encompasses a cross-connect as well as a switch in the strict sense of the term, references made to a switch in the remainder of the specification should be understood to

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mean a cross-connect or a switch, depending on the circumstances.

While an electrical switch provides adequate switching functionality for a low density of wavelength division multiplexing, i.e., to a small number of optical carriers per fiber, those skilled in the art will appreciate that as the density of a WDM optical network grows, it becomes prohibitively expensive (both pecuniarily and from the point of view of power consumption) to equip an electrical switch with sufficient optical-to-electrical and electrical-to-optical conversion resources to handle multiple incoming dense WDM signals arriving on their respective optical fibers.

To this end, the art has seen the development of the "photonic" switch (or cross-connect), which is the counterpart to the electrical switch (or cross-connect). In a photonic switch, switching is performed almost purely in the optical domain with only minimal recourse to optical-to-electrical or electrical-to-optical conversion. This advantageously results in significant reductions to the cost and complexity of the switching equipment.

A photonic switch can take on many generic forms, one of which is shown in Fig. 1 and more fully described in above-referenced co-pending U.S. Patent Application 09/511,065. The photonic switch 100 typically comprises N individual M-output wavelength division demultiplexing (WDD) devices 110_A-110_N, where each WDD device is associated with a respective one of N input fibers 120 connected to a respective set of N amplifiers 125. The photonic switch 100 also comprises N individual M-input wavelength division multiplexing (WDM)

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devices 130_A-130_N, one WDM device for each of N output optical fibers 140 connected to a respective set of N amplifiers 145.

5 The photonic switch 100 also comprises a photonic switch core 150 connected between the WDD devices 110_A-110_N and the WDM devices 130_A-130_N and a switch controller 160 connected to the photonic switch core 150.

10 On the input side of the photonic switch 100, each of the N WDD devices 110_A-110_N accepts a respective input WDM signal on a respective one of the input optical fibers 120. Each of the N WDD devices 110_A-110_N then separates the respective input WDM signal on a per-wavelength basis into a plurality (M) of input individual optical carrier signals which are provided to an input side of the photonic switch core 150 along a respective plurality (M) of demuxed input optical paths 170, which may consist of optical fibers, silica waveguides or other optical transmission media.

20 The photonic switch core 150 switches the input individual optical carrier signals, thereby to produce a plurality of switched individual optical carrier signals which are carried out of the photonic switch core 150 by a plurality of demuxed switched optical paths 180. The switch controller 160 generates a connection map under external or locally generated stimulus, which connection map is provided to the photonic switch core 150 and defines the desired map of the optical channels from the input side to the output side of the photonic switch core 150. External stimulus may be provided via a control link 165.

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At the output of the photonic switch core 150, each of the WDM devices 130_A-130_N receives a respective set of demuxed switched optical paths 180 and combines the switched individual optical carrier signals thereon into a single
5 respective WDM signal that exits the photonic switch 100 along a respective one of the output optical fibers 140.

In the illustrated embodiment, the photonic switch core 150 comprises a wavelength converting switch 190 and M optical switch matrices 150_A-150_M, one for each of the M optical wavelengths in the system. Each optical switch matrix has a set number of input ports and output ports and can be a Micro-Electro-Mechanical System (MEMS) device as described in "Free-Space Micromachined Optical-Switching Technologies and Architectures" by Lih Y. Lin of AT&T Labs-Research during OFC99 Session W14-1 on February 24, 1999. This article is incorporated by reference herein. Such a MEMS device comprises a set of mirrors that are arranged in geometrical relationship with the input and output ports such that incoming light from any input port can be diverted to any output port by erecting an appropriate one of the mirrors under control of the switch controller 160.

In Fig. 1, each of the optical switch matrices 150_A-150_M has a total of K+N input ports and K+N output ports where, it is recalled, N is the number of WDD devices 110_A-110_N and WDM devices 130_A-130_N. For each of the optical switch matrices 150_A-150_M, each of the N input ports will be connected to the like-wavelength output port of a respective one of the WDD devices 110_A-110_N, while each of the N output ports will be connected to the like-wavelength input port of a respective one of the WDM devices 130_A-130_N. This permits optical

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signals of a given wavelength entering a switch matrix 150_A-150_M to be connected to the appropriate port of any of the exiting WDM devices 130_A-130_N.

5 It is thus noted that each of the optical switch matrices 150_A-150_M has K more input ports and K more output ports than are required to switch the N corresponding input individual optical carrier signals (one of which arrives from each of the N WDD devices 110_A-110_N). These additional ports 10 are connected to the wavelength converting switch 190, with two important consequences. Firstly, optical carrier signals arriving on demuxed input optical paths 170 can be redirected towards the wavelength converting switch 190. Secondly, optical carrier signals arriving from the wavelength 15 converting switch 190 can be output onto one of the demuxed switched optical paths 180.

20 The net result is that a signal on an individual optical carrier is allowed to change wavelengths on its way through the photonic switch 100 by a process which involves optical reception, opto-electronic conversion, electrical switching of the converted electrical signal to an optical source at a desired wavelength and modulation of that source's optical output. The wavelength conversion process is particularly 25 useful when an input wavelength is already in use along the fiber path leading to a destination WDM device.

30 It should further be noted that the wavelength converting switch 190 also accepts a plurality of "add carriers" on a plurality (R) of add paths 192 and outputs a plurality of "drop carriers" on a plurality (R) of drop paths 194. Thus, it is seen that the wavelength converting switch 190 has a total of $((K \times M) + R)$ inputs and a like number of

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outputs. Structurally, the wavelength converting switch 190 comprises a set of $((K \times M) + R)$ electrical-to-optical converters, an electrical switch and a set of $((K \times M) + R)$ optical-to-electrical converters that collectively function as a miniature version of an electrical switch for optical signals.

The term "wavelength converting switch" will hereinafter be used throughout the following, with the understanding that such a switch may have either purely wavelength conversion capabilities or both wavelength conversion and add/drop capabilities.

In operation, the photonic switch 100 of Fig. 1 provides purely optical switching at the optical switch matrices 150_A - 150_M and wavelength conversion (most commonly through the use of electrical switching) at the wavelength converting switch 190. Control of which input individual optical carrier signals are redirected into the wavelength converting switch 190 is provided by the switch controller 160. The switch controller 160 also provides control of the switching executed inside the wavelength converting switch 190.

With the assistance of network-level control of the wavelengths used by the various sources in the network, it is usually possible to ensure that most wavelengths can transit directly across most nodes in the network without wavelength conversion, hence ensuring that the majority of optical carriers will be sent along the desired output optical fiber 140 directly by the optical switch matrices 150_A - 150_M without involving the wavelength converting switch 190. As a result, it is usually possible to achieve a minimal blocking probability at the photonic switch 100 by selecting a

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relatively small value for K, i.e., by keeping most of the switching entirely in the optical domain.

5 The photonic switch described in part herein above and described in more detail in co-pending U.S. Patent Application Serial No. 09/511,065 is an example of how developments in the field of optical switching are often stimulated by the need to accommodate the ever increasing optical wavelength density of WDM networks in general and WDM signals in particular.

15 In addition, the increase in density has driven up the cost associated with providing optical signal regeneration. This is largely due to the higher number of optical sources and receivers which must be provided at a regenerator site in order to handle the increased number of optical carriers per fiber, since each optical carrier has to be regenerated separately and independently. Consequently, those skilled in the art have begun to concentrate on lowering the cost of regeneration by trying to expand the reach between optical regeneration points in a dense WDM network.

25 The reach between optical regeneration points is limited by the build-up of degradation suffered by the optical carriers in the WDM signal which cannot be removed (and may actually be introduced) by current optical amplifiers. Specifically, the maximum reach attainable between first and second regeneration points is limited by factors such as:

- 30
- launch power and pulse shape at the first regeneration point;
 - receiver sensitivity at the second regeneration point;

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- build-up of uncompensated chromatic dispersion and polarization mode dispersion along the route;
- accumulation of noise arising from cascades of intervening amplifiers;
- 5 - excessive flat gain or loss of intervening amplifiers, WDM/WDD elements, connectors, splices and fibers;
- wavelength-dependent gain or loss through intervening amplifiers, WDM/WDD elements, connectors, splices and fibers; and
- 10 - cross-modulation and inter-modulation effects.

Many of the above factors contribute to producing a non-flat optical power spectrum of the WDM signal, i.e., the individual optical carriers will experience different amounts of gain and loss as they propagate. The resulting WDM signal with a non-flat optical power spectrum will reduce the maximum reach because optical carriers having higher power may saturate the intervening optical amplifiers, while 15 optical carriers having lower power may not be detected with sufficient accuracy by a far-end regenerator. Consequently, the power differential between high power carriers and low power carriers has to be minimize in order to maximize the reach between regenerators.

25 In attempting to solve this problem, it has been realized that for a conventional point-to-point WDM system, variations in the optical power of the component carriers of a WDM signal are often correlated between one optical carrier and its neighbours in the optical spectrum, due to having undergone a common, wavelength-dependent amplitude distortion process. Conventional spectrum flattening techniques take 30 advantage of this realization to provide "band equalization"

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of the power spectrum at an intermediate component between two regenerators. This type of equalization technique is now described with reference to Fig. 2.

5 Specifically, a band WDM device 4 may be used to separate an original WDM signal arriving on an input optical fiber 2 into a plurality of separate optical paths each consisting of a number of signals occupying mutually exclusive optical frequency bands. For simplicity of
10 illustration, there are three groups of signals occupying three bands denoted A, B, C, but there may be five bands in a typical band equalization scenario. The three separated groups of signals are still WDM signals in their own right but have fewer carriers than the original WDM signal.

15 Each of the three signals in bands A, B, C passes through a respective one of a plurality of variable optical intensity controllers (VOICs) 6, 8, 10. Each of the VOICs 6, 8, 10 could be an amplifier or an attenuator having a
20 response which is controllable within the band of interest but is irrelevant elsewhere. The outputs of the three VOICs 6, 8, 10 are then recombined by a band WDM device 12 into a recombined WDM signal provided on an output optical fiber 14.

25 In Fig. 2, the optical power spectrum of the original WDM signal on the input optical fiber 2 is shown at 16 and, in this example, is seen to comprise a total of fifteen optical carriers, five in each of the three broad optical frequency bands A, B, C. The correlation among the power
30 levels of neighbouring carriers in the input optical power spectrum 16 is apparent from the diagram.

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In addition, it is seen that the overall peak-to-peak power level variation (shown at 18) of the input optical power spectrum 16 is significant. However, because of the correlation among the power levels of neighbouring carriers, it is possible to identify an average power level 19A, 19B, 19C in each respective band such that the peak-to-peak power level variation with respect to that average power level in that band is reduced as compared to the overall peak-to-peak power level variation 18.

In order to achieve band equalization, the gain (or attenuation) to be applied by each of the VOICs 6, 8 and 10 is set to a value which complements the estimated average power level in the corresponding band in order to bring the average power level to a target level. Since the band equalization is usually a static technique, average power level estimates can be obtained at installation time. In the case of Fig. 2, comparing the average power levels 19A, 19B and 19C in bands A, B and C (which can be estimated at installation time), it is seen that VOIC 6 should be accorded a moderate gain, VOIC 8 should be accorded a high gain and VOIC 10 should be accorded a low gain.

25 After applying band equalization in the manner of Fig. 2, the optical power spectrum (shown at 20) of the recombined WDM signal provided on the output optical fiber 14 is seen to have a significantly lower overall peak-to-peak power level variation (shown at 22) when compared to the overall peak-to-peak variation 18 in the original WDM signal.

However, it will be apparent that the band equalization approach does not completely remove peak-to-peak variations in the optical power spectrum of the original WDM signal.

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5 Rather, it provides a mechanism for reducing the level of
variation and results in this level of reduction being traded
off against implementational complexity by exploiting the
correlation existing between adjacent carriers. Therefore,
as seen in Fig. 2, the resultant WDM signal travelling on the
output optical fiber 14 still contains wavelength-dependent
variations in its optical power spectrum 20.

10 Furthermore, the band equalization technique illustrated
in Fig. 2 does not account for wavelength-dependent power
level variations which may have been introduced by the band
demultiplexer 4 and the band multiplexer 12. Although not
explicitly shown in Fig. 2, the optical power spectrum 20 of
15 the output WDM signal could conceivably contain even more
significant variations due to the compounded effects of the
band demultiplexer 4 and the band multiplexer 12.

20 A further cause of variance in the optical power
spectrum of a WDM signal is the action of a photonic switch
such as that shown in Fig. 1. Specifically, because the
connection map of the photonic switch is arbitrary, being
driven by traffic connectivity considerations rather than
optical link considerations. Thus, a particular output WDM
signal emerging from the photonic switch will contain optical
25 carriers that will likely have travelled along entirely
different paths through the network. Each of these paths is
associated with its own loss characteristics and therefore
the various individual optical carrier optical signals that
make up a WDM signal at the output of the photonic switch
30 will have respective optical power level which are
uncorrelated with one another.

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The situation is illustrated in Fig. 3, where a 3x3 photonic switch 300 is connected to three input optical fibers 40, 42, 44 and three output optical fibers 60, 62, 64. The input optical power spectrum of the WDM signal on each of the input optical fibers 40, 42, 44 is shown at 50, 52, 54, respectively. Each of these three input optical power spectra 50, 52, 54 occupies the same optical frequency range but has a distinct shape. In particular, the shape of each of the optical power spectra 50, 52, 54 displays a certain degree of correlation among the power levels of neighbouring carriers. For example, spectrum 50 has a monotonically decreasing shape, spectrum 52 has a bell shape and spectrum 54 is composed of relatively constant power levels.

Since any arbitrary connection map may be provided by the photonic switch 300 at a given instant in time, the correlations existing among the carrier power levels on the input optical fibers 40, 42, 44 may not carry through to the output optical fibers 60, 62, 64. Hence, the output optical spectra (shown at 70, 72, 74) will exhibit a poor correlation among individual carriers and will appear "randomized". This effect may be compounded by differing losses experienced by the various signals as they transit the switch node components. Clearly, as a result of this lack of correlation among individual carriers, a band equalization technique such as that previously described with reference to Fig. 2 would be of little use if applied at the output or even at the input of the photonic switch 300.

Those skilled in the art will also appreciate that in addition to being affected by spectral variations arising from the arbitrary connection map applied by a photonic switch, the optical power spectrum of an output WDM signal

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may be further distorted by wavelength-dependent losses induced by a WDM device positioned at the output of the switch and, to a certain extent, by path-dependent losses through the photonic switch core.

Hence, it will be appreciated that the optical power spectrum of the WDM signals exiting a photonic switch can be severely distorted and, worse still, the distortion has no predictable spectral shape. Moreover, the optical power spectrum of the WDM signals can change dramatically and suddenly with each change in the connection map. Clearly, such wavelength-dependent distortion presents a serious limitation on the reach between the photonic switch and the next regeneration point in the network and therefore it would be a tremendous advantage to provide spectral flattening at the photonic switch, without adding significant complexity to the design of the photonic switch itself.

SUMMARY OF THE INVENTION

The present invention is directed to providing each signal at the output of a photonic switch with a controllable (e.g., flat) optical power spectrum, while only slightly increasing the complexity of the switch design. The equalization system, or "equalizer", of the present invention controllably adjusts the optical power of each individual optical signal passing through the photonic switch by placing a plurality of variable optical intensity controllers (VOICs) in each optical path prior to wavelength recombination. The VOICs can be variable optical amplifiers or variable optical attenuators. The VOICs are controlled by a controller which derives power estimates from individual optical carrier

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signals extracted from the WDM signals at the output of the photonic switch.

In this way, many advantages are achieved. Firstly, individual and independent control of the power on each optical channel is provided. Secondly, wavelength-dependent losses introduced by all the devices in the switch including the WDM devices at the output of the switch are accounted for. Thirdly, tapping the output WDM signals requires only one optical coupler for each output optical fiber, reducing the complexity of the equalization system. Fourthly, tapping the output WDM signals at the output of the switch has no effect on the system's noise floor.

In some embodiments of the invention, coarse equalization is provided for each multiplexed optical signal either at the input to the switch or at the output of the switch. This permits a reduction in the dynamic range over which the VOICs are required to operate, which advantageously allows the use of cheaper components.

In other embodiments of the invention, the controller in the equalizer will reduce the intensity of the individual optical signals that are effected by a forthcoming change in the connection map of the switch. The intensity is then gradually increased to a reference value once the new connection map is applied. This mapping procedure prevents existing carriers from being effected by sudden power level changes to other carriers sharing the same output optical fiber and optical amplifier chain.

In still other embodiments, the invention provides a calibration functionality. This can be achieved by

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evaluating the relative loss of each possible fiber/wavelength combination through the front end of the equalizer. In this way, spectral variations due to tolerances in the equalizer can be significantly reduced.

In a broad sense, the invention may be summarized as an optical intensity control system for use with an optical switch providing individual signal paths between a plurality of input ports and a plurality of output ports. The switch typically has a plurality of wavelength division multiplexers for combining sets of individual switched optical signals into multiplexed switched optical signals.

The intensity control system of the invention is equipped with a plurality of optical splitters, each being connectable to an output of a respective one of the wavelength division multiplexers and a plurality of variable optical intensity controllers (VOICs) for insertion into respective ones of the individual signal paths and for individually controlling the intensity of optical signals present in the respective ones of the individual signal paths in accordance with respective intensity control signals.

The intensity control system of the invention is further equipped with an equalizer connected to the splitters and to the VOICs, for producing an estimate of the optical power of each individual switched optical signal and generating the intensity control signals as a function of the estimates of optical power. This allows the optical powers of each of the carriers to be changed, resulting in a substantially equal power in each optical carrier.

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The equalizer may have a front end circuit with a plurality of inputs for receiving the multiplexed switched optical signals, where the front end circuit is adapted to controllably isolate individual switched optical signals from the multiplexed switched optical signals. The equalizer also has an optical receiver unit connected to the front end circuit, for converting any isolated individual switched optical signals to electrical signals. The equalizer is further equipped with a power estimation unit connected to the optical receiver unit, for time-averaging the electrical signals, thereby to obtain respective estimates of optical power. Finally, the equalizer has a processor connected to the power estimation unit and to the front end circuit, where the processor is adapted to cause the front end circuit to isolate selected individual switched optical signals and also to generate the intensity control signals from the estimates of optical power.

20 In some embodiments, front end circuit has wavelength-tunable optical bandpass filters connected to outputs of the optical splitters. The processor is then adapted to selectably tune the filters in order to cause individual switched optical signals to be selected on the basis of fiber origin and individual wavelength.

In other embodiments, the front end circuit is equipped with an optical switch matrix having a plurality of inputs respectively connected to the plurality of splitters and having a plurality of controllably erectable mirrors, as well as a wavelength division demultiplexer connected to an output of the switch matrix. In this case, the processor is adapted to selectably raise one mirror at a time on the optical

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switch matrix in order to cause selected individual switched optical signals to be isolated.

5 The front end circuit may alternatively comprise a first
optical switch matrix having a plurality of inputs
respectively connected to the plurality of splitters and
having a plurality of controllably erectable mirrors, as well
as a wavelength division demultiplexer connected to an output
10 of the first switch matrix and at least one second optical
switch matrix, where each second optical switch matrix has a
plurality of inputs connected to the wavelength division
demultiplexer and having a plurality of controllably
erectable mirrors. The processor would then be adapted to
15 selectably raise one mirror at a time on the first optical
switch matrix and to raise one mirror at a time on the at
least one second optical switch matrix in order to cause
selected individual switched optical signals to be isolated.

20 In still other cases, the front end circuit has (1) a
first optical switch matrix having a plurality of inputs
respectively connected to the plurality of splitters and
having a plurality of controllably erectable mirrors, (2) a
wavelength division demultiplexer connected to an output of
the first switch matrix, (3) at least one second optical
25 switch matrix, each the second optical switch matrix having a
plurality of inputs connected to the wavelength division
demultiplexer and having a plurality of controllably
erectable mirrors and (4) a coupler connected to an output of
each second optical switch matrix.

30 The invention may also be broadly summarized as a method
of generating control signals for adjusting the intensity of
single-carrier optical signals travelling through an optical

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switch, wherein groups of individual switched optical signals are recombined into multiplexed switched optical signals at an output end of the switch. The method includes the steps of:

- (a) controllably isolating individual switched optical signals from the multiplexed switched optical signals;
- (b) estimating the power of the individual switched optical signals isolated at step (a); and
- (c) generating the control signals as a function of the power estimates obtained at step (b) and a reference value.

The invention can also be broadly summarized as a switch for optical signals, which has wavelength division demultiplexers, wavelength division multiplexers, optical splitters connected to the multiplexer output port of a respective one of the wavelength division multiplexers, a switching core connected between the wavelength division demultiplexers and the wavelength division multiplexers, a plurality of variable optical intensity controllers (VOICs) positioned in respective ones of the optical paths, and an equalizer as described above, connected to the couplers and to the VOICs.

The switching core may comprise a plurality of core optical switching matrices, each core optical switch matrix being associated with a distinct optical wavelength. The switching core may further comprise a wavelength-converting inter-matrix switch connected to the core optical switching matrices, for receiving optical signals from the core optical switching matrices, converting each received optical signal to electrical form and transmitting each converted signal at

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a changed wavelength to the core optical switch matrix associated with the changed wavelength.

If optical switch matrices are used in the equalizer, at least one such optical switch matrix can be in a stacked relationship with respect to one or more core optical switch matrices to improve compactness.

The invention may also be summarized broadly as a method of calibrating power estimates received at a processor connected to an optical carrier selection circuit in an intensity control loop. The method includes the steps of:

obtaining a reference estimate of the optical power of a reference light source without the effect of the optical carrier selection circuit;

controlling the optical carrier selection circuit in order to obtain an estimate of the optical power of the reference light source for each of a plurality of possible optical paths through the optical carrier selection circuit;

generating a calibration factor for each path by evaluating a function of the difference between the corresponding received power estimate and the reference estimate; and

adjusting subsequent power estimates for each path by the corresponding calibration factor.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other aspects and features of the present invention will now become apparent to those of ordinary skill in the art upon review of the accompanying description of specific embodiments of the invention in conjunction with the following drawings, in which:

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Fig. 1, already described, shows a photonic switch in block diagram form;

Fig. 2, already described, shows in block diagram form an implementation of a band equalization technique;

Fig. 3, already described, shows the effects of a photonic switch on the power spectrum of a WDM signal at the output of the photonic switch;

Fig. 4 shows in block diagram form part of a photonic switch in accordance with an embodiment of the present invention;

Figs. 5 through 9 show, in block diagram form, specific embodiments of an equalizer forming part of the photonic switch of Fig. 4;

Fig. 10 shows a message flow diagram between controllers inside and outside the equalizer under transient conditions;

Fig. 11 is a table illustrating a comparative summary of the component requirements of the embodiments of Figs. 5 through 9;

Fig. 12 is a block diagram of an embodiment of the photonic switch of the invention which uses coarse intensity control at the input to the switch;

Fig. 12A shows a variation of the embodiment of Fig. 12;

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Fig. 13 is block diagram of another embodiment of the photonic switch of the invention which uses coarse intensity control at the input to the switch;

Fig. 14 is a block diagram of an embodiment of the photonic switch of the invention which uses coarse intensity control at the output of the switch;

Fig. 15 is a block diagram of an embodiment of the photonic switch of the invention with calibration functionality; and

Fig. 16 shows the application of calibration functionality to the embodiment of Fig. 12A.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

With reference to Fig. 4, there is shown a photonic switch 400 according to an embodiment of the present invention. The photonic switch 400 resembles the photonic switch 100 of Fig. 1 in that it retains the basic structure including the WDD devices 110_A-110_N , the WDM devices 130_A-130_N and the photonic switch core 150.

The photonic switch 400 of the invention additionally comprises a plurality ($M \times N$) of variable optical intensity controllers (VOICs) 410 respectively positioned in each of the demuxed switched optical paths 180. Thus, each of the VOICs 410 is associated with a respective switched individual optical carrier signal that emerges from the photonic switch core 150 along a respective one of the demuxed switched optical paths 180.

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5 The VOICs 410 are used for providing intensity control in the form of either attenuation or amplification. Thus, each of the VOICs 410 can either be a variable optical attenuator or a variable optical amplifier, depending on the operational requirements of the invention. The range of intensity control (i.e., attenuation or gain) required of an individual VOIC is typically expected to be on the order of 8 decibels (dB) or less, although it is within the scope of the invention to provide a greater or smaller dynamic range of
10 attenuation or gain.

15 It is convenient to view the VOICs 410 as forming an array of size $M \times N$ where, it is recalled, N is the number of WDM devices 130_A-130_N and M is the number of wavelengths handled by each WDM device (which is also the number of optical switch matrices 150_A-150_M in the photonic switch core 150). Typical values for M are 32 and above, while typical values for N are 4 and above. However, it should be understood that the invention is not subject to any
20 limitation on M or N .

25 Each of the VOICs 410 has a control port for receiving a respective intensity control signal along a respective one of a plurality of intensity control lines generally indicated by the reference numeral 415. Each such intensity control line carries an intensity control signal indicative of a desired amount of attenuation or gain to be applied by the respective VOIC. The intensity control line leading to the VOIC corresponding to the J^{th} optical switch matrix 150_J and the
30 K^{th} WDM device 130_K can be denoted $415_{J,K}$, where $J \in \{A, B, \dots, M\}$ and $K \in \{A, B, \dots, N\}$.

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With continued reference to Fig. 4, the photonic switch 400 of the invention further comprises a plurality (N) of directional couplers 420 (also referred to as optical splitters), each of which intercepts the optical path of a respective one of the N output optical fibers 140. It is noted that the number of couplers 420 is equal to the number of output optical fibers 140, which is M times less than the total number of demuxed switched optical paths 180.

It should be understood that the couplers (splitters) 420 could be placed after the amplifiers 145 (as shown) or in front of the amplifiers 145, depending on the operational requirements of the invention. For instance, if it is important to allow openness so that 3rd party amplifiers 145 can be used, then it is desirable to place the couplers 420 in front of the amplifiers 145. However, such a configuration would not permit the power spectrum equalizer 500 to compensate for spectral gain variations introduced by the amplifiers 145. Therefore, to compensate for such variations, it would be advantageous to place the couplers 420 after the amplifiers 145.

Each of the N couplers 420 can be a standard component which is designed to tap a small, known amount of optical power from the respective output optical fiber 140. A suitable amount of optical power tapped in this manner will be 10 dB to 13 dB below the optical power level on the respective output optical fiber 140. This lowers the optical power level of the ongoing signal by only 0.22 dB to 0.46 dB, which loss can then be compensated for by increasing the gain of the respective amplifier (when the couplers 420 are placed in front of the amplifiers 145) or by increasing the gain

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(decreasing the attenuation) of the VOICs 410 associated with that amplifier.

The photonic switch 400 of the present invention further comprises a power spectrum equalization control system (hereinafter simply referred to as an "equalizer") 500 which is placed between the couplers 420 and the VOICs 410 and which communicates with a switch controller 160' via a control line 440. The switch controller 160' is similar to the switch controller 160 in Fig. 1 with additional special operational features that will be described later on. As with the switch controller 160 of Fig. 1, the switch controller 160' of Fig. 4 communicates with the outside world by a control link 165.

The equalizer 500 is connected to each of the N couplers 420 by a respective one of a plurality of optical paths 425_A-425_N, where optical path 425_A carries a tapped WDM optical signal from WDM device 130_A, optical path 425_B carries a tapped WDM optical signal from WDM device 130_B, and so on. The equalizer 500 is further connected to the control port of each of the MxN VOICs 410 by a respective one of the plurality of intensity control lines 415.

The equalizer 500 may have a variety of internal configurations, some of which will be described in further detail later on. A feature common to each structure is the provision of suitable circuitry, software and/or control logic for:

- receiving tapped optical signals from the couplers 420 along the optical paths 425_A-425_N;

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- processing the tapped optical signals according to an algorithm (still to be described); and
- generating intensity control signals to be supplied to the $M \times N$ individual VOICs 410 via the $M \times N$ intensity control lines 415.

Thus, the equalizer 500 controls the amount of gain or attenuation to be applied by each of the VOICs 410. This is done with the aim of flattening the optical power spectrum of each output WDM signal.

Specific embodiments of the equalizer 500 are now described with reference to Figs. 5, 6, 7, 8 and 9. In Fig. 5, the equalizer 500 is seen to comprise N individual M -output WDD devices 510_A-510_N , each of which is connected to a respective one of the couplers 420 via a respective one of the optical paths 425_A-425_N . Each of the WDD devices 510_A-510_N is designed to separate the received, coupled version of the respective output WDM signal into its M individual optical carrier components. Therefore, the M signals at the output of each of the WDD devices 510_A-510_N correspond to the M switched individual optical carrier signals as combined by the respective one of the WDM devices 130_A-130_N .

Each of the WDD devices 510_A-510_N is connected to a respective set of M optical receivers. For notational convenience, the particular optical receiver associated with the switched individual optical carrier signal carried along one of the demuxed switched optical paths 180 from the j th optical switch matrix 150_j to the K^{th} WDM device 130_K can be denoted $520_{j,K}$. Thus, in Fig. 5, WDD device 510_A is connected to optical receivers $520_{A,A}$, $520_{B,A}$, ... $520_{M,A}$,

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WDD device 510_B is connected to optical receivers 520_{A,B}, 520_{B,B}, ... 520_{M,B}, etc., and WDD device 510_N is connected to optical receivers 520_{A,N}, 520_{B,N}, ... 520_{M,N}.

5 The optical receivers (collectively denoted by 520) each comprise circuitry such as a photodiode and a trans-impedance amplifier for converting into electrical form an optical signal present at its input. In the embodiment of Fig. 5, 10 the signal received at the input to a given optical receiver is always at the same wavelength, and therefore each of the optical receivers 520 can be a narrow-optical-bandwidth component tuned to the appropriate optical wavelength.

15 The MxN optical receivers 520 are respectively connected to a plurality (MxN) of power estimation modules. The individual power estimation module connected to optical receiver 520_{J,K} for a particular value of J and K can be denoted by 530_{J,K}. Thus, the power estimation module denoted by 530_{A,A} is connected to optical receiver 520_{A,A}, and so on. 20

Each of the power estimation modules (collectively denoted by 530) comprises circuitry, firmware or control logic for estimating the power of the optical signal from which the electrical signal received from the respective one 25 of the optical receivers 520 was derived. Since optical power is directly proportional to optical intensity, suitable power estimation circuitry could include circuitry for measuring the average voltage of the received electrical signal, from which the optical power can be determined. Of 30 course, those skilled in the art will be familiar with other methods of power estimation. Furthermore, sampling and

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digitizing operations can be performed either prior or subsequent to power estimation.

It will also be appreciated that as long as the digital signal on each optical wavelength has a duty cycle of approximately 50% (i.e., has an approximately equal number of zeroes and ones over a pre-determined integration interval), the receivers 520 and power estimation modules 530 can be low-speed components for measuring average power over such an integration interval.

With continued reference to Fig. 5, the power estimate produced by each of the power estimation modules 530 is provided to a respective input of a controller 550. In the embodiment of Fig. 5, the controller 550 is equipped with a MxN-input multiplexer 552 which is connected to a processor 554. The processor 554 selectively reads the power estimates through control of the multiplexer 552 via a control line.

The processor 554 comprises suitable circuitry, software and/or control logic for processing the power estimates received from the power estimation modules 530 and generating intensity control signals for transmittal to the VOICs 410 along the intensity control lines 415. Operation of the processor 554 in accordance with an equalization algorithm will be described in further detail later on.

As shown in Fig. 5, the processor 554 may be connected to the VOICs by a plurality (MxN) of latches 556 and an intervening demultiplexer 558. Thus, the processor 554 may provide the intensity control signals one at a time to the demultiplexer 558 along a single signal line. Under control of the processor 554, the demultiplexer 558 then sends the

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received intensity control signal to the appropriate one of the latches 556, where the present value of the intensity control signal is held until further notice.

Another specific embodiment of the equalizer 500 is shown in Fig. 6. In this case, the equalizer 500 comprises a plurality of wavelength-tunable optical bandpass filters 610_A-610_N , each of which is connected to a respective one of the couplers 420 via a respective one of the optical paths 425_A-425_N . A wavelength-tunable optical bandpass filter is a known component which passes a selectable optical frequency range of an input signal as a function of a control voltage or current supplied to the filter. Thus the need for WDD devices at the input to the equalizer 500 can be avoided, while reducing the total required number of optical receivers and power estimation modules.

Specifically, the output of each of the wavelength-tunable optical bandpass filters 610_A-610_N is connected to a respective one of a plurality of optical receivers 620_A-620_N , each of which is similar to one of the optical receivers 520 previously described with reference to Fig. 5. However, because the signal input to any one of the N optical receivers 620_A-620_N may occupy any one of the M possible wavelengths in the system, the optical receivers 620_A-620_N must each be operable over a wider optical bandwidth, typically the entire WDM spectrum.

Each of the optical receivers 620_A-620_N has an output which is connected to a respective one of a plurality of power estimation modules 530_A-530_N , each of which is identical to any of the power estimation modules suitable for

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use in the equalizer of Fig. 5. The power estimation modules 530_A-530_N are connected to respective inputs of a controller 650. In the embodiment of Fig. 6, the controller 650 is equipped with an N-input multiplexer 652 which is connected to a processor 654. The processor 654 selectively reads the power estimates through control of the multiplexer 652 via a control line.

The processor 654 comprises suitable circuitry, software and/or control logic for processing the power estimates received from the power estimation modules 630 and generating intensity control signals for transmittal to the VOICs 410 along the intensity control lines 415. In addition, the controller 650 comprises a filter driver 656 for varying, under control of the processor 654, the pass band of the wavelength-tunable optical bandpass filters 610_A-610_N via a respective plurality of control lines 615_A-615_N. Operation of the processor 654 in accordance with an equalization algorithm will be described in further detail later on.

The processor 654 may be connected to the VOICs by a plurality (MxN) of latches 556 and an intervening demultiplexer 558. Thus, the processor 654 provides the intensity control signals one at a time to the demultiplexer 558 along a single signal line. Under control of the processor 654, the demultiplexer 558 then sends the received intensity control signal to the appropriate one of the latches 556, where the present value of the intensity control signal is held until further notice.

Another specific embodiment of the equalizer 500 is shown in Fig. 7, wherein the optical paths 425_A-425_N lead to respective inputs of an N-input optical switch matrix 710

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(e.g., a MEMS based optical switch matrix as described in the previously referenced article by Lih Y. Lin of AT&T Labs-Research) which can be identical to any one of the switch matrices 150_A-150_M in Fig. 4. In this case, only one of the output ports of the optical switch matrix 710 is used and this particular output port is connected to an M-output WDD device 510. However, it is possible to decrease response and scanning times by using more than one output of the optical switch matrix 710, with each such output being connected to its own WDD device.

Within the optical switch matrix 710 there is provided an arrangement of N controllably erectable mirrors 712_A-712_N. The position of each mirror is either flat (in the plane of the optical switch matrix 710) or upright (perpendicular to the plane of the optical switch matrix 710), depending on the value of a control signal 714. When a particular one of the mirrors 712_A-712_N, say the pth mirror 712_p, is selected to be upright, then light arriving along the corresponding optical path 425_p from the corresponding one of the couplers 420 will be directed to the output of the optical switch matrix 710 and into the WDD device 510.

The WDD device 510 is identical to the WDD devices 510_A-510_N of Fig. 5 and thus is designed to separate the received optical signal (arriving from the optical switch matrix 710) into its M component wavelengths. The signals output by the WDD device 510 arrive at respective ones of a plurality of optical receivers 520_A-520_M.

Since each of the optical receivers 520_A-520_M is dedicated to processing signals having a fixed wavelength,

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each of the optical receivers 520_A-520_M can have a narrower optical bandwidth than the receivers 620_A-620_N in Fig. 6. Thus, each of the optical receivers 520_A-520_M can be identical to any of the optical receivers suitable for use in the equalizer of Fig. 5 and is accordingly designated by the same reference character. The number of such optical receivers in the embodiment of Fig. 7 is equal to the number of wavelengths (which is M).

Each of the optical receivers 520_A-520_M is connected to a respective one of a plurality of power estimation modules 530_A-530_M , each of which can be identical to any of the power estimation modules suitable for use in the embodiments of Figs. 5 and 6. The number of power estimation modules 530 in the embodiment of Fig. 7 is equal to the number of wavelengths (M). The power estimation modules 530_A-530_M are connected to respective inputs of a controller 750. In the embodiment of Fig. 7, the controller 750 is equipped with an M-input multiplexer 752 which is connected to a processor 754. The processor 754 selectively reads the power estimates through control of the multiplexer 752 via a control line.

The processor 754 comprises suitable circuitry, software and/or control logic for processing the power estimates received from the power estimation modules 530_A-530_M and generating intensity control signals for transmittal to the VOICs 410 along the intensity control lines 415. In addition, the controller 750 comprises a switch driver 758 for raising, under control of the processor 754, a selected one of the mirrors 712_A-712_N in the optical switch matrix 710. Operation of the processor 754 in accordance with an

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equalization algorithm will be described in further detail later on.

5 As was described earlier with reference to Figs. 5 and 6, the processor 754 may be connected to a plurality (MxN) of
latches 556 by a demultiplexer 558. Thus, the processor 754 provides the intensity control signals one at a time to the
demultiplexer 558 along a single signal line. Under control
10 of the processor 754, the demultiplexer 558 then sends the received intensity control signal to the appropriate one of the latches 556, where the present value of the intensity control signal is held for the respective VOIC until further notice.

15 In Fig. 8 is shown yet another embodiment of the equalizer 500 of the present invention, representing an elegant simplification in the design. In this embodiment, there is provided a first N-input optical switch matrix 710 (identical to that of Fig. 7) which is connected to a WDD
20 device 510 (identical to those of Figs. 5 and 7). The elevation of a particular mirror in the optical switch matrix 710 is controlled by a control signal received along a control line 714. The output of the optical switch matrix 710 contains a multi-wavelength optical signal which is split
25 into its M optical carrier components by the WDD device 510.

The WDD device 510 is connected to one or more additional N-input optical switch matrices 710'. Each of the
30 optical switch matrices 710' consists of an arrangement of controllably erectable mirrors whose position is either flat or upright as controlled by another control signal received along another control line 714'. Thus, only one output of each of the optical switch matrices 710' is actually used.

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Of course, in order to use only one N-input optical switch matrix 710', then N (the number of input or output optical fibers) should be greater than or equal to M (the number of wavelengths in the system). Since in many cases this condition cannot be satisfied, it becomes necessary to provide a number of optical switch matrices 710' equal to $\text{ceil}(M \div N)$, where $\text{ceil}(M \div N)$ represents the smallest integer value not less than the quotient of M and N.

The case where $\text{ceil}(M \div N) = 2$ is shown in Fig. 8, there being provided two optical switch matrices 710' with the output of each optical switch matrix being coupled together at a coupler 810. Alternatively, the coupler 810 can be omitted and the output of each of the switch matrices 710' can be provided to a controller 850 via separate paths. In either case, by ensuring that only one of the mirrors on only one of the optical switch matrices 710' is upright at any one time, the multiple optical switch matrices 710' can be made to behave as a single M-input optical switch matrix.

An advantage of using multiple N-input optical switch matrices 710' rather than one M-input optical switch matrix is that N-input optical switch matrices 710' have the exact same dimensions as the optical switch matrices 150_A-150_M in the photonic switch core 150 and can be fully integrated therewith. Thus, the optical switch matrices 710, 710' can be stacked or aligned with respect to the optical switch matrices 150_A-150_M in the photonic switch core 150, thereby improving compactness of the switch as a whole.

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5 The output of the coupler 810 is connected to the optical receiver 620 which can be identical to any of the optical receivers previously described with reference to Fig. 6., i.e., the optical receiver 620 must have a sufficiently wide optical bandwidth of operation to handle optical carrier signals occupying different wavelengths at different times. If the coupler 810 is dispensed with, then the output of each of the optical switch matrices 710' could be connected to its own wide-optical-bandwidth optical receiver.

10 The optical receiver 620 is connected to a power estimation module 530, which can be identical to any of the power estimation modules suitable for use in the embodiments of Figs. 5, 6 and 7. If the coupler 810 is omitted from the design, then the number of optical receivers and power estimation modules would equal the number of optical switch matrices 710', which is equal to $\text{ceil}(M+N)$.

15 The power estimation module 530 is connected to an input of a processor 854 in the controller 850. The processor 854 comprises suitable circuitry, software and/or control logic for processing power estimates received from the power estimation module 530 and generating intensity control signals for transmittal to the VOICs 410 along the intensity control lines 415. Moreover, the controller 850 comprises a switch driver 858 for raising, under control of the processor 854, exactly one of the mirrors 712_A-712_N in the optical switch matrix 710 and exactly one of the mirrors from among all those in the one or more optical switch matrices 710' connected to the WDD device 510. This allows the processor 854 to sequentially access the individual power estimates associated with various wavelength-fiber combinations. Operation of the processor 854 in accordance with an

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equalization algorithm will be described in further detail later on.

As was described previously with reference to Figs. 5 through 7, the processor 854 may be connected to a plurality (MxN) of latches 556 by a demultiplexer 558. Thus, the processor 854 provides the intensity control signals one at a time to the demultiplexer 558 along a single signal line. Under control of the processor 854, the demultiplexer 558 then sends the received intensity control signal to the appropriate one of the latches 556, where the present value of the intensity control signal is held until further notice.

Still another embodiment of the equalizer 500 is depicted in Fig. 9, wherein there is provided an N-input optical switch matrix 710 much like any of the previously described optical switch matrices suitable for use in the embodiments of Figs. 7 and 8. The selection of which of the mirrors 712_A-712_N is to be raised is controlled via a control link 714. An output of the optical switch matrix 710 is connected to a single wavelength-tunable optical bandpass filter 610 much like any of the filters 610_A-610_N suitable for use with the embodiment of Fig. 6. Again, the use of more than one output of the optical switch matrix 710 may reduce the response and scanning time associated with measuring the power of the switched individual optical carrier signals travelling through the photonic switch 400.

30 The output of the wavelength-tunable optical bandpass filter 610 is connected to a processor 954 within a controller 950 via a wide-optical-bandwidth optical receiver 620 and a power estimation module 530. The processor 954 is equipped with suitable circuitry, software and/or control

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logic for processing power estimates received from the power estimation module 530 and generating intensity control signals for transmittal to the VOICs 410 along the intensity control lines 415.

Moreover, the controller 950 comprises a switch driver 958 for raising, under control of the processor 954, exactly one of the mirrors 712_A-712_N in the optical switch matrix 710. In addition, the controller 950 comprises a filter driver 956 for varying, under control of the processor 954, the pass band of the wavelength-tunable optical bandpass filter 610 via a control link 615. This allows the processor 954 to sequentially access the individual power estimates associated with various wavelength-fiber combinations. Operation of the processor 954 in accordance with an equalization algorithm will be described in further detail later on.

As was described previously with reference to Figs. 5 through 8, the processor 954 may be connected to a plurality (MxN) of latches 556 by a demultiplexer 558. Thus, the processor 954 provides the intensity control signals one at a time to the demultiplexer 558 along a single signal line. Under control of the processor 954, the demultiplexer 558 then sends the received intensity control signal to the appropriate one of the latches 556, where the present value of the intensity control signal is held until further notice.

Fig. 11 provides, in tabular form, a comparative summary of the various embodiments of the controller in Figs. 5 through 9 in terms of the number of components (optical receivers, power estimation modules, optical switch matrices, WDD devices, wavelength-tunable optical bandpass filters)

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required in order to implement each embodiment. It is seen that the progression of embodiments from Fig. 5 through to Fig. 9 is increasingly intricate yet elegant. The utmost in simplicity and elegance is achieved in the embodiment of Fig. 9 where the equalizer 500 requires only one power estimation module 530, one wavelength-tunable optical bandpass filter 610, one wide-optical-bandwidth optical receiver 620 and one N-input switch matrix 710.

As has been previously described (with reference to Fig. 8, for example), the use of N-input optical switch matrices 710, 710' permits these switch matrices to be integrated into the structure of the photonic switch core 150. Thus, in designing a card cage for housing the optical switch matrices 150_A-150_M forming part of the optical switch core 150, it is within the scope of the invention to provision additional slots not only for use with spare optical switch matrix cards but also for use with the optical switch matrix cards 710, 710' needed by the equalizer (e.g., 1 spare card for the embodiments of Figs. 7 and 9 and $\text{ceil}(M \div N)$ spare cards for the embodiment of Fig. 8).

Operation of the "equalization processor" is now described. The term "equalization processor" is hereinafter used to refer to any of the processors 554, 654, 754, 854, 954 previously described with reference to Figs. 5, 6, 7, 8, 9, respectively. In each case, the equalization processor runs an equalization algorithm for processing the power estimates received from the power estimation module(s) 530 and for interacting with the switch controller 160' via the control line 440.

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5 The equalization algorithm has two modes of operation, the first mode being a so-called "scan mode", which is executed under steady-state connection conditions, and the second mode being a so-called "directed mode", which is entered upon interruption of the equalization controller while it is running in scan mode.

In scan mode, operation of the equalization controller basically consists of:

- (1) cycling through all "valid" combinations of output optical fibers and wavelengths, and reading the power estimate associated with each such valid combination; and
- (2) adjusting, as a function of the power estimates, the intensity control signals being fed to the VOICs.

20 A "valid" combination referred to in (1) above means that an optically carrier modulated data signal is expected to be found on that particular wavelength and on that particular output optical fiber.

Typically, at any given instant, many combinations of output optical fiber and wavelength will be valid but some will not, i.e., it is expected that one or more wavelengths on one or more output optical fibers may not contain an optical carrier modulated data signal. Whether or not a particular combination is valid depends on the connection map and thus will be known to the switch controller 160'. The switch controller 160' can therefore make available a list of valid combinations to the equalization processor. This list

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is then kept up to date in a manner to be described further on when discussing the "directed mode" of operation.

Having determined that a particular combination of wavelength and output optical fiber is indeed valid, the equalization processor, still in step (1) of scan mode, must read the power estimate corresponding to this combination. The manner in which this is achieved depends on the configuration of the controller as a whole. For example, let the equalization processor be required to access the power estimate associated with the J^{th} wavelength on the K^{th} output optical fiber.

15 In the embodiment of Fig. 5, the equalization processor 554 would obtain the desired power estimate by reading the output of power estimation module 530_{J,K}, which is uniquely associated with the desired combination of wavelength and output optical fiber.

20 In the embodiment of Fig. 6, the equalization processor 654 sends a message to the filter driver 656, which then instructs the k^{th} wavelength-tunable optical bandpass filter 610_k to pass light occupying the j^{th} wavelength. The equalization processor 654 would then obtain the desired
25 power estimate by reading the output of the k^{th} power estimation module 530_k.

In the embodiment of Fig. 7, the equalization processor 754 sends a message to the switch driver 758, which then instructs the optical switch matrix 710 to raise the k th mirror 712 $_k$. The equalization processor 754 would then

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obtain the desired power estimate by reading the output of the j^{th} power estimation module 530_j.

In the embodiment of Fig. 8 (with the coupler 810 in place), the equalization processor 854 sends a message to the switch driver 858, which then instructs the switch matrix 710 to raise only the k th mirror and also instructs the appropriate one of the optical switch matrices 710' to raise only the j th mirror. The equalization processor 854 would then obtain the desired power estimate by reading the output of the power estimation module 530.

Finally, in the embodiment of Fig. 9, the equalization processor 954 sends a first message to the switch driver 958, which then instructs optical switch matrix 710 to raise the K^{th} mirror 712_K. The equalization processor 954 also sends a second message to the filter driver 956, which instructs the wavelength-tunable optical bandpass filter 610 to pass light occupying the J^{th} wavelength. The equalization processor 954 would then obtain the desired power estimate by reading the output of the power estimation module 530.

Now having regard to step (2) above, namely the adjustment of the intensity control signals being fed to the VOICs 410 as a function of the power estimates, the scan mode of operation provides for at least two ways of performing this step.

30 In a preferred version of step (2) in scan mode operation, the received power estimate associated with a valid combination (e.g., the J^{th} wavelength on the K^{th} output optical fiber) is immediately compared to a pre-determined

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reference value, and the resulting difference is encoded as an intensity control signal that is fed to the demultiplexer 558. The demultiplexer 558 is then controlled to send this intensity control signal to the appropriate one of the latches 556, which is then used to drive the appropriate VOIC via the appropriate intensity control line 415_{J,K}.

This procedure is repeated for each valid combination of wavelength and output optical fiber. After a finite time, the output power level of each carrier on each output optical fiber will converge to the respective desired output power level.

In an alternate version of step (2) in scan mode of operation, all the power estimates associated with valid wavelengths on the K^{th} output optical fiber are read, following which a reference output power level for the carriers on the K^{th} output optical fiber is computed.

Next, the difference between the reference output power level and the power estimate associated with a particular valid wavelength (e.g., the J^{th} wavelength) on that K^{th} output optical fiber is fed as an intensity control signal to the demultiplexer 558. The demultiplexer 558 is then controlled to send this intensity control signal to the appropriate one of the latches 556, which is used to drive the appropriate VOIC via the appropriate intensity control line 415_{J,K}.

This procedure is repeated for each output optical fiber (i.e., for each value of K). After a finite time, the output power level of each carrier on each output optical fiber (i.e., for each set of J and K corresponding to a valid

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combination) will have converged to the appropriate reference output power level.

It will be appreciated that either version of the scan mode of operation described above provides gain flattening which advantageously compensates for unequal and uncorrelated power levels among the carriers which would otherwise have occurred due to the arbitrary connection map applied by the photonic switch core 150 under control of the switch controller 160'.

Furthermore, it is noted that the optical power of each carrier is estimated only after the carrier has already exited the respective one of the WDM devices 130_A-130_N, located at the output of the photonic switch 400. Thus, the power equalization provided by the present invention is also capable of compensating for wavelength-dependent losses introduced by the WDM devices 130_A-130_N as well as for and path-dependent losses through the photonic switch core 150.

Moreover, because only N couplers 420 are required and because each such coupler is associated with only one of the output optical fibers 140, another advantage of the invention is that the requirements on the tolerance of the couplers 420 need not be severe. This is due to the fact that variations in the flat loss between couplers causes a constant amplitude error across all wavelengths existing on a given fiber and therefore does not affect the spectral flatness. Moreover, such errors in the flat loss can be compensated for in the line system amplifiers 145, if the couplers 420 are placed in front of the amplifiers 145 and if the amount of compensation is within the amplifiers' dynamic range.

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Having described the scan mode of operation, the need for a directed mode of operation arises in the situation where the controller 160' is ready to instruct the photonic switch core 150 to apply a new connection map. That is to say, a directed mode of operation is required when (I) one or more combinations which were previously not valid are now considered to be valid or (II) when valid connections are rearranged. The reason for this is that suddenly adding new carriers or rearranging existing carriers can result in the disruption of those carriers which remain in service unchanged, due to the possibility of the new or rearranged optical carriers causing a sudden change in the optical amplifier gain or causing non-linear optical effects.

Accordingly, as shown in Fig. 10, the directed mode of operation is entered when an INTERRUPT message 1010 is received by the equalization processor from the switch controller 160'. The INTERRUPT message 1010 is indicative of the fact that a new connection map is about to be established by the switch controller 160'. Specifically, the INTERRUPT message 1010 contains the identity of (A) all the combinations which are currently not valid but which will become valid as a result of the upcoming change to the connection map; (B) all the combinations which are currently valid but which will become invalid as a result of the upcoming change to the connection map; and (C) all the combinations which are currently valid and which are about to be rearranged.

Upon receipt of the INTERRUPT message 1010, the equalization processor enters an initialization routine 1020, whereupon the equalization processor proceeds to read the power estimate associated with: (i) each presently invalid but soon-to-be valid combination of wavelength and output

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optical fiber; and (ii) each presently valid and soon-to-be rearranged combination of wavelength and output optical fiber. The equalization processor then confirms that there is no carrier present on the combinations identified under (i) above. For the purposes of the reading the power estimate of a particular invalid but soon-to-be valid combination, it is understood that the respective intensity control signal should be set to a reasonable value (i.e., not to minimum gain / maximum attenuation).

Next, the equalization processor enters a neutralization routine 1030. Specifically, for each combination under (i) and (ii) above, the respective intensity control signal is ramped down to a value which provides minimum gain (or maximum attenuation, as appropriate). Setting the intensity to minimum gain / maximum attenuation is done in order to prevent the onset of disruptions to other carriers on the same output optical fiber upon adding the new or rearranged carrier, while the ramping down process mitigates the onset of disruptions to these other carriers during execution of the neutralization routine 1030 itself.

After having completed the neutralization routine 1030, the equalization processor sends a PROCEED message 1040 to the switch controller 160', authorizing it to proceed with the establishment of the new connection map. In response to receipt of the PROCEED message 1040, the switch controller 160' applies the new connection map at step 1050 and sends an ACKNOWLEDGE message 1060 back to the equalization processor. The ACKNOWLEDGE message 1060 indicates that the new connection map has been established.

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In response to receipt of the ACKNOWLEDGE message 1060, the equalization processor proceeds to execution of a ramping routine 1070. The ramping routine 1070 consists of increasing the power level of each carrier that was neutralized in the neutralization routine 1030, i.e., each carrier associated with (a) each previously invalid but now valid combination of wavelength and output optical fiber; and (b) each previously valid and now rearranged combination of wavelength and output optical fiber. This increase in power level can be effected by increasing the value of the intensity control signal for each VOIC associated with a previously neutralized carrier from its minimum gain / maximum loss value (previously set in the neutralization routine 1030) to a value which brings the corresponding individual optical carrier signal to the same optical power level as the other individual optical carrier signals sharing the same output optical fiber.

As the value of the intensity control signal is being changed, the power estimates received from the power estimation module(s) will change and should therefore be given time to converge to new values. Hence, it is desirable to raise or lower the value of the appropriate intensity control signal in a gradual fashion, e.g., by ramping. The result of this ramping process will be to reduce the risk of affecting those wavelengths that already carry high speed optical data signals and that are not allowed to be disturbed.

Finally, before exiting the directed mode of operation, the equalization processor executes an update routine 1080, which consists of updating its list of valid and invalid combinations, based on the information in the INTERRUPT message

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1010. (It is recalled that this list is consulted by the equalization processor while running in scan mode.) The equalization processor subsequently returns to scan mode.

5 Thus, through operation of the equalization processor in directed mode and interaction of the equalization processor with the switch controller 160', the present invention achieves the advantage of reducing disruptions to existing carriers due to changes in the connection map involving the
10 addition or rearranging of one or more carriers on one of more output optical fibers.

Those skilled in the art will appreciate that many other embodiments are within the scope of the invention. For
15 instance, instead of gradually decreasing and then increasing the power of each new or rearranged carrier, such carriers could be removed or introduced in an incremental fashion, i.e., in groups of one or two, etc. Thus, the neutralization routine 1030 could be represented by a process in which one
20 intensity control signal at a time (or two intensity control signals at a time, etc.) is gradually or suddenly decreased to a minimum gain / maximum attenuation value.

Similarly, the ramping routine 1070 could be replaced by
25 a procedure whereby the affected carriers are introduced one by one without the need for ramping but with a suitable delay between the introduction of each new carrier in order to allow the power estimates to converge to new values. The gradual introduction of carriers still reduces the risk of
30 causing a hit on those wavelengths which already carry high speed optical data signals and which should not be disturbed.

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Fig. 12 shows another variant of the photonic switch 400 of Fig. 4 which provides "coarse" intensity control at the input to each WDD device in the photonic switch 400. Specifically, a tap coupler (splitter) 1220 and a VOIC 1210 intercept each input optical fiber 120, between the respective amplifier 125 and the respective one of the WDD devices 110_A-110_N.

Each VOIC 1210 applies relatively flat gain or attenuation which affects all wavelengths on the given input optical fiber 120 to substantially the same degree. Thus, each VOIC 1210 should be capable of operating over a wider optical bandwidth than required for any of the VOICs 410. The amount of attenuation or gain to be applied by each VOIC 1210 is encoded by a respective intensity control signal arriving along a respective intensity control line 1250 from a plurality of latches 1256. The latches 1256 are driven by a demultiplexer 1258 that is fed by a co-processor 1254.

In the coarse equalization scheme of Fig. 12, the amount of gain or attenuation to be applied by each VOIC 1210 is controlled such that the aggregate optical power of the optical signal on each input optical fiber 120 is approximately the same before entering the respective one of the WDD devices 110_A-110_N. In order to measure this aggregate optical power, each tap coupler 1220 is connected by a respective optical path 1240 to a respective input of a common N-input optical switch matrix 1230.

The optical switch matrix 1230 can be identical to the switch matrices 710, 710' described with respect to Figs. 7-9. It consists of a plurality of mirrors which can be controllably raised or lowered in order to let through the

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optical signal present on a selected one of the optical paths 1240. Control of the raising and lowering of mirrors in the optical switch matrix 1230 is achieved by the co-processor 1254 via an intervening switch driver 1235.

An output of the optical switch matrix 1230 is connected to an optical receiver 1260, which comprises circuitry such as a photodiode and a trans-impedance amplifier for converting into electrical form the optical signal present at its input. In the embodiment of Fig. 12, the signal received at the input to the optical receiver 1260 occupies multiple wavelengths and therefore the optical receiver 1260 must have a wide optical bandwidth of operation.

The output of the optical receiver 1260 is connected to a power estimation module 1270 which can be identical to any of the power estimation modules 530 suitable for use with the embodiments of Figs. 5 through 9. The output of the power estimation module 1270 is fed to the co-processor 1254.

In operation, the co-processor 1254 (which can function independently of any of the processors 554, 654, 754, 854, 954 or can be integrated therewith) controls the raising and lowering of the mirrors in the optical switch matrix 1230 via the switch driver 1235 in order to obtain an aggregate power estimate, one input optical signal at a time, from the power estimation module 1270. The co-processor 1254 then compares each received power estimate to a reference and the difference is applied to the appropriate VOIC 1210 through control of the demultiplexer 1258 and the appropriate one of the latches 1256.

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Thus, the co-processor 1254 strives to maintain all the aggregate input power levels at substantially the same value in a feed-forward fashion. In general, this coarse power level adjustment will produce a significant reduction in the spread among optical power levels on a particular output optical fiber 140, with the consequence that the dynamic range of the VOICs 410 (which are controlled by processor 554, 654, 754, 854 or 954) can be significantly reduced. This reduction in required dynamic range allows the use of less expensive VOICs 410 in each switched demuxed optical path 180.

It is also within the scope of the invention to provide coarse power equalization at the input end in the manner of a true feedback loop as shown in Fig. 12A. For improved performance, the order of the tap couplers 1220 and the VOICs 1210 along each input of the optical fibers 120 can be reversed as shown. Greater disparities in the loss of the various VOICs 1210 can then be tolerated due to the power level measurements having been obtained via the tap couplers 1220 following (rather than before) application of intensity control by the VOICs 1210. When designing the feedback loop, however, those skilled in the art will of course recognize that special attention must be paid to stability concerns.

Those skilled in the art will also appreciate that in Figs. 12 and 12A, the optical switch matrix 1230 and its associated switch driver 1235 can be omitted without affecting the way in which the coarse equalization scheme works. Specifically, it is within the scope of the invention to provide separate sets of optical receivers 1260 and power estimation modules 1270 in each optical path 1240. Any individual power estimate could then be accessed by the co-

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processor 1254 via a common intervening multiplexer (not shown).

Other coarse equalization schemes can be implemented. For example, the couplers 1220, the optical switch matrix 1230, the switch driver 1235, the optical receiver 1260 and the power estimation module 1270 can be dispensed with while still providing coarse equalization at the input through the action of the VOICs 1210. Such an embodiment is shown in Fig. 13, where the co-processor (1254 in Fig. 12) and processor (554, 654, 754, 854, 954 in Figs. 5-9) have been integrated into a single equalization processor 1354 in the equalizer 500'. As a result of the radical hardware simplification of the embodiment of Fig. 13 with respect to the embodiment of Fig. 12, the algorithm being run by the equalization processor 1354 is slightly more complex.

Specifically, the equalization processor 1354 operates in scan mode until it is interrupted by the switch controller 160', whereupon the equalization processor 1354 enters a directed mode of operation.

The actions performed by the equalization processor 1354 in directed mode, in respect of preparing for the appearance of a new or re-arranged carrier, remain unchanged from those described previously. However, it is the equalization processor's routine operation in scan mode which is slightly more complex because the equalization processor 1354 controls the amount of intensity variation applied by not one but both sets of VOICs 1210 and 410. Specifically, in each pass through the algorithm in scan mode, the equalization processor 1354 does not compute the "fine" gain or attenuation to be applied by the VOICs 410 until it has

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computed the "coarse" gain or attenuation to be applied by the VOICs 1210.

Since the power estimates available to the equalization processor 1354 are typically post-switching power estimates, and since the coarse intensity control is performed by the VOICs 1210 prior to switching, the controller 1354 must invert the connection map applied by the controller 160' in order to determine the amount of coarse intensity control it should apply at the input in order to result in a reduction in the power spread on each output optical fiber 140. Different ways of inverting a connection map will be known to those skilled in the art.

Practically, the equalization processor first determines the required gain for each individual demuxed switched optical path in the already described manner, and then determines how much of this gain or attenuation is common to all paths originating from the same input optical fiber. The common amount of intensity control is applied to the appropriate one of the VOICs 1210 and the remaining amount of intensity control for each demuxed switched optical path is applied to the appropriate VOIC 410.

In this way, the dynamic range required to be handled by the VOICs 410 can be significantly reduced, because each VOIC will only have to supply a residual amount of gain or attenuation. Thus, the hardware requirements are reduced with respect to the embodiment of Fig. 12, at the expense of a slight increase in computational complexity with respect to the controller 1254.

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Of course, a similar coarse equalization scheme can be applied at the output of the WDM devices 130_A-130_N, prior to tapping by the couplers 420. This embodiment is shown in Fig. 14, where each of the output optical fibers 140 is intercepted by a respective one of a plurality of VOICs 1410_A-1410_N placed between a respective one of the WDM devices 130_A-130_N and the respective coupler 420.

In the case of Fig. 14, each of the VOICs 1410_A-1410_N applies a coarse amount of intensity control to all the wavelengths of the associated output optical fiber 140. Hence, the equalization processor 1454 in the equalizer 500'' would determine the amount of required intensity control which is common to all wavelengths sharing an output optical fiber, would apply the common amount of intensity control to the appropriate one of the VOICs 1410_A-1410_N and would apply the amount of residual gain or attenuation to the appropriate VOICs 410.

Again, the dynamic range required to be handled by the VOICs 410 can be significantly reduced, because each will only have to supply a residual amount of gain or attenuation. This can significantly reduce the aggregate cost of the VOICs 410, at the expense of a slight increase in computational complexity with respect to the equalization processor 1454 in the equalizer 500''. In fact, this embodiment is even simpler than the embodiment of Fig. 12 or Fig. 13 because it does not require knowledge of the connection map through the photonic switch core 150.

Further modifications and refinements of the above-described embodiments are within the scope of the invention. In particular, it is recalled that the embodiments of Figs.

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5, 7 and 8 employ WDD devices 510 within the equalizer 500 and the embodiments of Figs. 7, 8 and 9 use one or more optical switch matrices 710, 710'. Due to the wavelength-dependent loss characteristics of the WDD devices 510 and due to path-dependent loss characteristics of the optical switch matrices 710, 710', it should be apparent that power level variations may be introduced by these components, depending on the specific path taken by light travelling from the couplers 420 to the equalization controller 500. Hence, losses inherent to the measurement process itself may distort the power estimates produced by the power estimation module(s) 530.

A solution to this problem is provided in Fig. 15, which illustrates an equalizer 1500 with a front end 1502, an optical receiver bank 1504, a power estimation module bank 1506 and an equalization controller 1510 which collectively encompass the embodiments previously described with reference to Figs. 5 through 9. Additionally, the equalizer 1500 is equipped with calibration functionality. Specifically, in order to enable the computation of the loss of each possible path from the output optical fibers 140 to the equalization controller 1510, there is provided a calibration source 1520 for providing light of a desired wavelength and at a desired gain. The calibration source 1520 is fed by the equalization processor 1554 in the equalization controller 1510.

At the output of the calibration source 1520 is provided an (N+1)-way splitter 1530, which sends the incoming light from the calibration source 1520 along N+1 different optical fibers 1540_A-1540_N, 1550. Optical fibers 1540_A-1540_N are coupled via a respective plurality of couplers 1560_A-1560_N to the N optical paths 425_A-425_N leading from the couplers 420.

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Optical fiber 1550 leads directly to the controller 1510 via an attenuator 1570, an optical receiver 1580 and a power estimation module 1590. The attenuator 1570 provides a fixed attenuation to account for the loss through the (N+1)-way splitter 1530.

In operation, the equalization processor 1554 operates in scan mode until the switch controller 160' indicates that it is about to change the connection map through the photonic switch core 150. Operation of the equalization processor 1554 in scan mode is virtually the same as previously described with reference to Figs. 5 through 9, with one main variation.

Specifically, after evaluating the difference between a desired power level and the estimated power of a signal associated with a particular combination of wavelength and output optical fiber, the equalization controller 1510 adjusts this difference by a "calibration factor" associated with the path of that signal from the associated one of the couplers 1560_A-1560_N to the equalization controller 1510 through the front end 1502.

The "calibration factor" associated with a path represents the inverse of the relative loss of that path. One way in which the equalization processor 1554 may determine the calibration factor of a particular path through the front end 1502 is as follows:

- select a wavelength;
- instruct the calibration source 1520 to emit at that wavelength;

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- instruct the front end 1502 to pass through the desired wavelength along the desired path;
- read from the power estimation module bank 1506 the power estimate corresponding to the desired wavelength arriving along the desired path;
- read the power estimate received from the power estimation module 1590;
- determine the difference between the two values and store the result as the calibration factor for that particular path.

The calibration factor of each path is not expected to change with time, since the properties of the components located between the couplers 1560_A-1560_N are not expected to change. Thus, the calibration step can be performed during an initialization phase. Still, in order to apply the appropriate calibration factor, it is necessary for the equalization processor 1554 to maintain an updated mapping of which combination of output optical fiber and wavelength is associated with which path.

By adjusting the intensity control signals provided to the VOICs 420 by the above-introduced calibration factors, the present invention as embodied in Fig. 15 advantageously compensates for errors which may otherwise have been introduced by the measurement process. Of course, it should be understood that the calibration is accurate to the degree that the properties of the optical receiver 1580 and power estimation module 1590 approximate those of the components in the optical receiver bank 1504 and the power estimation module bank 1506.

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It should be appreciated that the calibration scheme of Fig. 15 can also be used in order to calibrate individual optical paths through either of the coarse equalization schemes previously described with reference to Fig. 12 or 12A. The application of the calibration scheme of Fig. 15 to the coarse equalization scheme of Fig. 12A is shown in Fig 16, where the couplers 1560_A-1560_N are connected to the optical paths 1240 leading from the tap couplers 1220 connected to the input optical fibers 120. It is noted that the calibration source 1620 is a multi-colored light source which spans the same optical frequency range as any of the input WDM signals on the input optical fibers 120.

The co-processor 1654 operates as previously described with reference to Fig. 12. However, after evaluating the difference between a desired power level and the estimated power of an input WDM signal associated with a particular input optical fiber, the co-processor 1654 adjusts this difference by a "calibration factor" associated with that input optical fiber. This "calibration factor" represents the inverse of the relative loss of the path travelled by light coming from that input optical fiber through the associated one of the couplers 1560_A-1560_N and through the optical switch matrix 1230.

One way in which the co-processor 1654 may determine the calibration factor of a particular path through the optical switch matrix 1230 is as follows:

- select an input optical fiber;
- instruct the calibration source 1620 to emit multi-colored light;

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- instruct the optical switch matrix 1230 to pass through any light along the selected input optical fiber;
- read from the power estimation module 1270 the power estimate corresponding to the selected input optical fiber;
- read the power estimate received from the power estimation module 1590;
- determine the difference between the two values and store the result as the calibration factor for that particular input optical fiber.

The calibration factor associated with each input optical fiber is not expected to change with time, since the properties of the components located between the couplers 1560_A-1560_N are not expected to change. Thus, the calibration step can be performed during an initialization phase.

It is seen that by adjusting the intensity control signals provided to the VOICs 1210 by these calibration factors, the present invention as embodied in Fig. 16 advantageously compensates for errors which may otherwise have been introduced during measurement of the intensity of each input WDM signal.

A further variation of the present invention involves placing the VOICs 410 at the input (rather than at the output) of the photonic switch core 150. Knowledge of the connection map would then be required in order to determine which of the switched individual optical carrier signals are combined by which WDM devices 130_A-130_N. Also, it may be desirable in such a scenario to account for the dB loss of

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each signal through the photonic switch core 150, which loss would be constant so long as the connection map remains constant and would change as the connection map changes. Since this change is usually predictable to a good degree of accuracy, the equalization processor can adjust the intensity control signal supplied to each of the VOICs 410 by the respective known loss through the switch core 150.

In other embodiments of the invention, the output of the optical receivers 520 could be connected to functional units other than a power equalization system, such as a path integrity analyzer described in the co-pending U.S. Patent Application to Graves et al., entitled "Optical Switch with Connection Verification" and filed on even date. Of course, this assumes that the optical receivers 520 have sufficient electrical bandwidth to meet the functional requirements of the path integrity analyzer.

While specific embodiments of the present invention have been described and illustrated, it will be apparent to those skilled in the art that still further modifications and variations can be made without departing from the scope of the invention as defined in the appended claims.